# Study of Solar Chromosphere: Variation of Calcium K line profiles with Solar cycle

A Synopsis of Thesis

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by

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# Summary

Solar chromosphere is the thin layer between the photosphere and the corona that can be viewed during the occurrence of total solar eclipse as crimson red ring surrounding the moon or observed using astronomical techniques. Chromosphere can be studied in detail using spectra or spectroheliograms in some of the Fraunhoffer solar lines originating in the chromosphere such as H-alpha, Ca-K line and few others. These lines are formed in the solar atmosphere at different heights between 200 - 2000 kms above the photosphere and represent temperature in the range of 10000- 20000$^{\circ}$ K. The images of the Sun in Ca-K line show chromospheric features like plages, network and internetwork. The plages are formed due to the presence of magnetic fields surrounding the sunspots. The horizontal velocity of about 0.3 Kms/ second in large convective cells (supergranules) carries the flux tubes to the boundaries and deposit these there. The concentration of magnetic field lines there causes increase in emission in Ca-K line at the boundaries and thereby showing the network. The Ca-K emission depends on the magnetic flux density in that region (Ortiz and Rast, 2005; Nindos and Zirin, 1998).

The reliable long term photospheric variability have been investigated photometrically by making measurements with radiometers from space based instruments as the ground based measurements do not provide accurate data for such a study as variation is $\pm$ 0.1% (Frohlich et al, 1998) only with the phase of solar cycle. The long term variations in the chromosphere have been studied mostly by measuring the plage areas in the Ca-K line images (Worden et al, 1998; Tlatov et al, 2009; Foukal et al, 2009; Ermolli et al, 2009; Priyal et al, 2013). The other method to investigate the long term variability of solar chromosphere is to study the Ca-K line profile parameters of the Sun as a star with time (White and Livingston, 1978; Oranje, 1983; Keil and Worden, 1984; Sivaraman et al, 1987). The Ca-K line profiles vary with time due to varying contribution not only from plages but also from the enhanced, active and quiet network. To study the variations in the Ca-K line profiles, locations such as $K_{1v}$, $K_{2v}$, $K_3$, $K_{1r}$, $K_{2r}$ (see Figure 1) are identified in the line profiles by locating the minima and maxima of intensity. Then we can determine the various parameters of the line in terms of widths and intensity ratios as defined below:
$K_1$ width: $K_1$ width is defined as the wavelength separation between the $K_{1v}$ and $K_{1r}$ minima.
$K_2$ width: $K_2$ width is defined as the wavelength separation between the $K_{2v}$ and $K_{2r}$ emission peaks.
Wilson-Bappu width: The wavelength difference of the two wavelength positions cor-

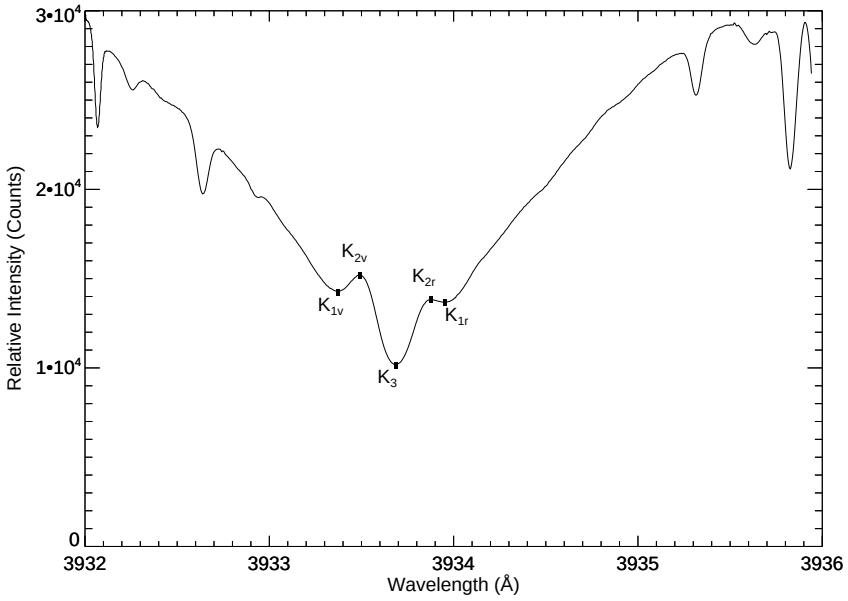


Figure 1: Typical Ca-K line profile of the Sun obtained using the high resolution spectrograph at Kodaikanal tunnel telescope. The K line parameters are marked on the line profile.

responding to ($IK_{1r}$+$IK_{2r}$)/2 and ($IK_{1v}$+$IK_{2v}$)/2 gives Wilson-Bappu width.
Other parameters of interest are the derivation of Ca-K line indices, namely 1 Å and 0.5 Å index and intensity ratios $K_{2v}/K_3$, $K_{2v}/K_{1v}$, $K_{2r}/K_3$, $K_{2r}/K_{1r}$.

Skumanich et al (1984) proposed a three component model of variability of Ca-K emission using extent contrast and functional area parameters, with cell, network and plage. They were able to fit the model profile with the observed one during the minimum phase of solar cycle but could not during maximum phase. Hence, they introduced an additional component to match the profiles during the maximum phase and named it as "active network component". But the measurements made over the centre of the solar disk over a region of $1'' \times 3''$ showed no variation with solar cycle phase (White and Livingston, 1978). Therefore the new method of observing at different solar latitude integrated over 180° longitude was started (Singh, 1989). By this method we have obtained Ca-K line profile at every 10° interval for both the hemispheres for the period of 1985-2011. The detector used for the period 1985-1997 is photographic films and 1997 onwards CCD (Photometrics or Andor). For the data

with the photographic film density to intensity conversion is done using the step wedge calibration taken on the same day of observations. After dark and flat field correction of data obtained with the CCD and density to intensity conversion of the data with photographic film, the average profiles over 10° have been computed. Then wavelength calibration is done using the two photospheric absorption lines due to Fe I 3932.826 and 3935.682 ÅȦll the line profiles were normalized using residual intensity at 3935.16 Å on the red wing of the Ca-K line as 13% of the continuum intensity (White and Suemoto, 1968). Then the Ca-K line parameters were determined from the Ca-K line profile.

After deriving various parameters of Ca-K line profiles over intervals of 10°, to begin with we have derived the $K_1$ and $K_2$ widths for the Sun as a star by determining the average of widths over all the latitudes (hereafter called KKL) observation to compare the KKL values with Kitt peak and NSO/Sac peak data (Sindhuja and Singh, 2014a). This was done because they have made observations of the Sun as a star which means average Ca-K line profile over all the latitudes and longitudes whereas in KKL observations integration is done over longitudes only. We found that the mean of $K_1$ and $K_2$ widths for all the three data sets are about 0.635 $\pm$ 0.005 Å and 0.370 $\pm$ 0.005 Å respectively indicating a correlation and accuracy in measurements made at all the three observatories. Standard deviation values of $K_1$ (0.039 $\pm$ 0.001 Å) and $K_2$ widths (0.011 $\pm$ 0.001 Å) for Kodaikanal and Kitt peak data are found to be in agreement but those of NSO/Sac peak differs being 0.048 and 0.017 Å for $K_1$ and $K_2$ widths, respectively. It may be noted that average value of $K_1$ width during the maximum phase of the solar cycle 22 and 23 is 0.673 Å for cycle 22 and 0.672 Å for cycle 23 as obtained from the yearly mean data after outliers removal but is lower and different during the minimum phase. Generally it has been observed that occurrence of sunspots and related chromospheric activity such as Ca-K plages cause variations in the irradiance and Ca-K line parameters during the active phase of the solar cycle. But we find that yearly mean $K_1$ width is larger (0.58 $\pm$ 0.01 Å) during the minimum phase of cycle 22 as compared to the average value (0.55 $\pm$ 0.01 Å) during the minimum phase of cycle 23 after removal of outliers from the data. The smaller value of $K_1$ width during the minimum phase of cycle 23 may be because of extended nature of the minimum phase of this cycle. On an average both $K_1$ width and plage areas are more during the maximum phase as compared to those during the minimum phase of the solar cycle. But day to day variations in the $K_1$ and $K_2$ widths and plage areas do not occur with similar magnitude and thus cause large amount of scatter in the plot of $K_1$ width versus plage areas. This implies that irradiance variations may occur not only due to large scale solar activity but also because of variations in small scale activity due to enhanced, active and intra-network in quiet regions of the Sun. The variation

in intensity of the plages can also cause day to day variations in widths.

The study of the variation of Ca-K line parameters as a function of latitude during minimum and active phases separately will help to deliniate the role of different features of the chromosphere and global variations if any. The left panel in Figure 2 shows variation of Ca-K line parameters with latitude during minimum phase (2007) and right panel shows parameters for the data taken during maximum phase (2000). The bars in the Figure 2 shows the standard deviation (SD) due to day to day variations in the values, not the error in measurements which is very small $< 5$ mÅ . The spread in the values, represented by bars in Figure 2, of Ca-K line parameters during the maximum phase is large as compared to that during the minimum period due to large day to day variations during the maximum phase of the solar cycle. As expected $K_1$ and $K_2$ widths and other parameters of the Ca-K line show variations with latitude due to variation of toroidal component of magnetic field depending upon the activity during the maximum phase of the solar cycle and due to the inherent properties of latitude caused by the limb darkening effect. The variation in the Ca-K line parameters with latitude during the minimum phase of solar cycle occur due to centre to limb effect only as no sunspots and related activity such as plages are visible on the solar surface (Athay and Skumanich, 1968). Due to centre to limb effect one sees upper layers of the chromosphere at the edges of the Sun as compared to the centre. The increase in temperature with height in chromosphere causes increase in width of the Ca-K line with latitude as the Ca-K line profile originates in higher parts of the chromosphere at larger latitudes. Hence, $K_1$ width is expected to increase with increasing distance from the centre of the Sun as one observes higher in the chromosphere at higher temperature at larger distance from the centre. But the Figure 2 shows that there are some variations in the Ca-K line parameters in addition to those with latitude. The Figure 2 indicates that the values of $K_1$ and W-B widths, $K_3$ intensity, K1.0 and K0.5-indexs are larger at 5° southern latitude as compared to those at the adjacent latitudes. The larger values of these parameters indicate more activity around 5° latitude belt which may be due to small scale activity due to Ca-K network as no sunspots were seen on the solar surface during the period of observations or some global pattern. In addition, all these parameters indicated sharper increase in the values with latitude in the southern hemisphere as compared to the increase in the northern hemisphere. The ratio of $K_{2v}$ to $K_3$ intensity shows increase with latitude up to about 60° latitude but the value of this ratio decreases in the polar region as compared to that at 60° latitude. Similarly the ratio of $K_{2v}$ to $K_{2r}$ intensity remains more or less the same up to 60° latitude and decreases in the polar regions.

To compare the values for the two phases we have plotted value of $K_1$ width

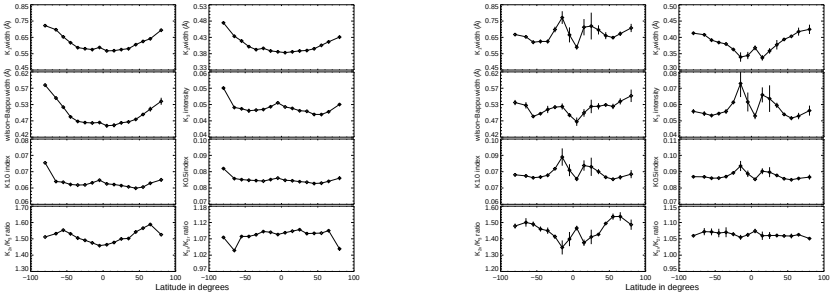


Figure 2: *Left* The variation of Ca-K line parameters with latitude during 2007 (minimum phase) and *Right* for the year of 2000 (maximum phase). The figure shows large changes in the Ca-K line parameters in the region of up to 30° latitude apart from the latitudinal variation due to occurrence of activity because of torodial component of magnetic field during the period of maximum phase (2000)

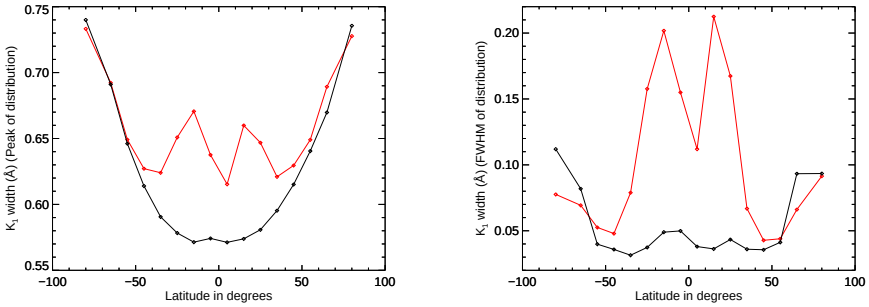


Figure 3: *Left* shows most probable value of $K_1$ width defined by the peak of Gaussian fit to the distribution of $K_1$ width for the active phase in red and for minimum phase in black for various latitudes. *Right* shows range of $K_1$ width defined by the FWHM of the Gaussian fit to the distribution of $K_1$ widths.

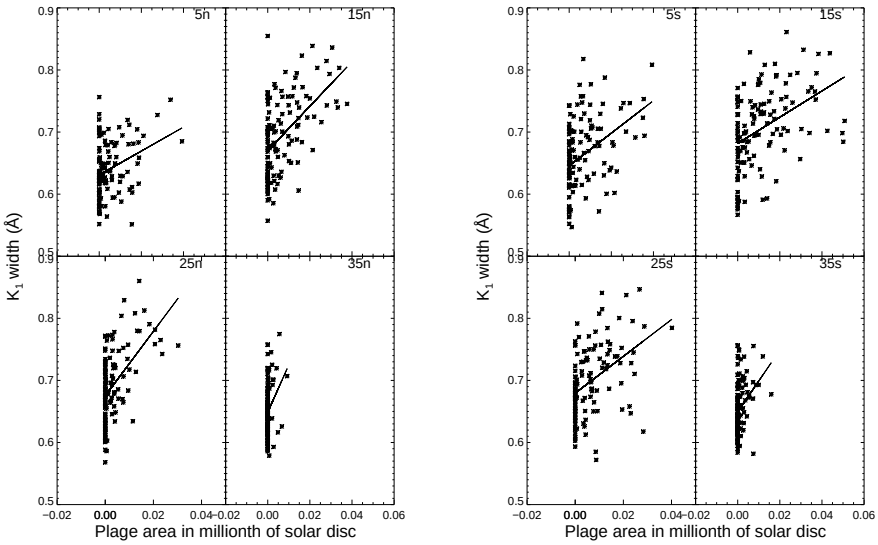


Figure 4: *Left* Plot of $K_1$ width vs plage area in millionth of solar disc for 5°, 15°, 25° and 35° north latitudes for the years 1989 - 1992 and 2000 - 2005 around the active phase *Right* Same for southern hemisphere

(the peak of Gaussian curve) and FWHM in Figure 3 as a function of latitude for the active and minimum phase of the solar cycle. Left side panel of Figure 3 show that the values of $K_1$ width for the activity phase are larger by about 10-15% than those for the minimum phase for the equatorial region up to $\sim 35^\circ$ latitude. Then the difference in values at the activity and minimum phase goes on decreasing up to 55° latitude and the values of $K_1$ width become similar around 65° latitude. But in the polar regions $K_1$ width is 1-2% smaller during the active phase than that at minimum phase indicating more activity at polar region during the minimum phase as compared to that during the active phase of solar cycle. The range of variation, represented by the FWHM of the Gaussian fit, in $K_1$ width also shows the similar behaviour as the $K_1$ width indicated in the right side panel of Figure 3. We find that remnant $K_1$ width ($K_1$ width at latitudes when plages were not visible on the solar surface) at middle and lower latitudes representing the small scale (network) solar activity is more during the maximum than that during the minimum phase of the solar cycle.

Assuming a linear relation between the $K_1$ width and the plage area and after accounting for this variation, we find that the scatter in the values of $K_1$ width on the day to day basis is large see Figure 4. This appears to be caused by variations in different features with different time scales as listed by Scargle et al (2013). Therefore,

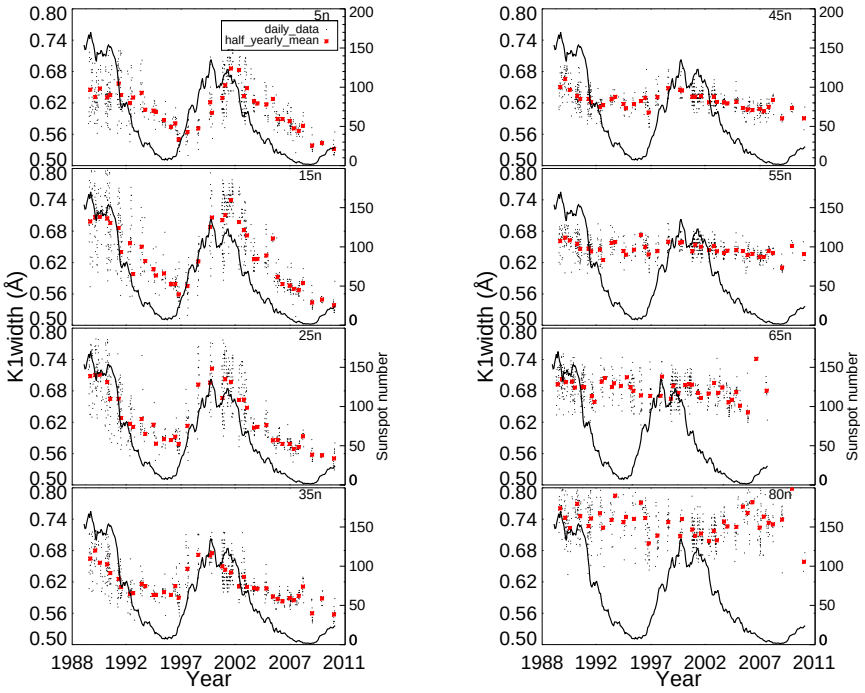


Figure 5: The $K_1$ widths averaged over 10° latitude and 180° longitude, at an interval of 10° are plotted as a function of time for the northern hemisphere on daily basis (black dots) for the period of 1989 - 2011 that covers about 2 solar cycle, Half yearly mean values of $K_1$ width are shown as red astericks and the half yearly Greenwich averaged sunspot numbers (solid line) have also been plotted for comparison. Average latitude for the plot is indicated at the top right side of each panel.

contribution due to variation in the small scale activity caused by the network need to be considered in the study of irradiance variation with solar cycle phase. More number of days data per year and better resolution in latitude are needed to confirm the variations in small scale activity during the different phases of solar cycle. The measurements of $K_1$ and $K_2$ widths of Ca-K profile with latitude and time indicates asymmetry in the northern and southern hemisphere and confirms the extended minimum phase of the solar cycle 23.

The plots of $K_1$ width with time for different latitudes (Figure 5) at an interval of 10°, density histograms of $K_1$ width at all latitudes and cross correlation of $K_1$ width which represents the activity at various latitudes with those of 35° latitude belt

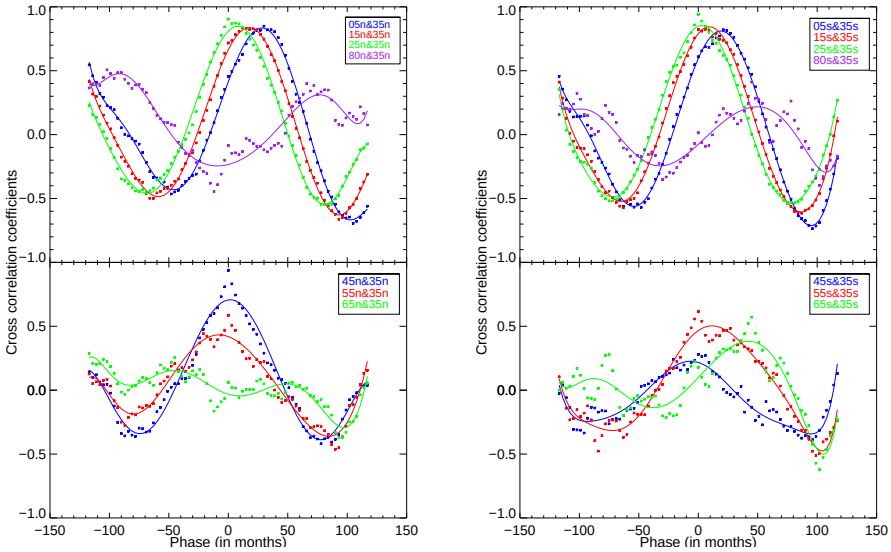


Figure 6: The cross-correlation coefficients of $K_1$ width at 35° latitude with that at other latitude belt as a function of phase difference. *Top left* is for 5° (blue), 15° (red), 25° (green) and 80° (purple) northern belts with 35° northern latitude belt and *Bottom left* for 45° (blue), 55° (red) and 65° (green) northern latitude belts. *Top and bottom right* are for southern hemisphere, respectively. Solid curves are polynomial fits to the coefficients.

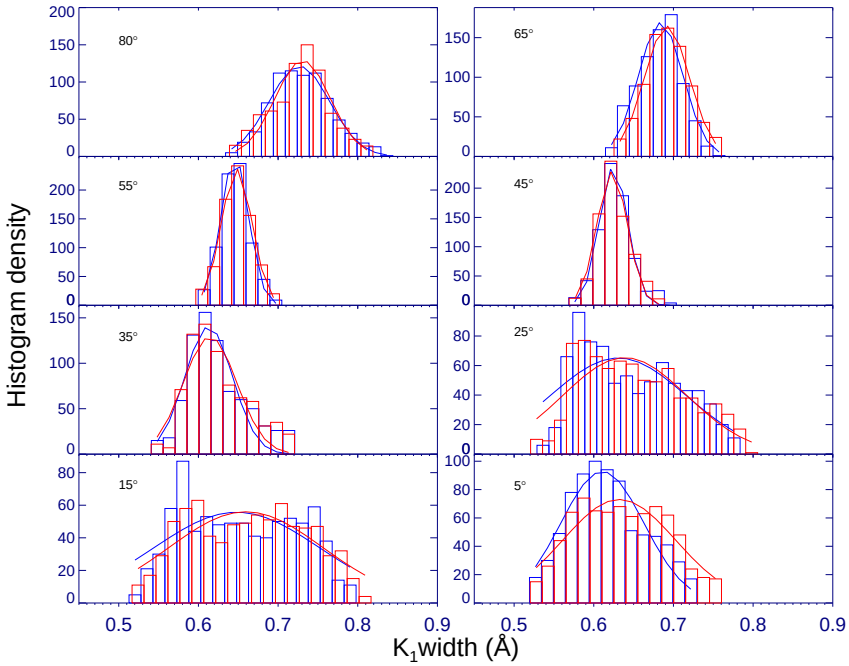


Figure 7: Histograms of the distribution of $K_1$ widths in blue and red are for northern and southern hemispheres respectively with bin size of 0.015 Å . Gaussian fit curves are also plotted in respective colours. The mean latitude of the distribution is shown in each panel.

(Figure 6) (Sindhuja et al, 2014b), indicate that:
(1) the method of observations is effective to study the latitudinal variation as a function of solar cycle and especially polar region.
(2) no symmetry in the northern and southern hemispheres in terms of the speed of shifting of activity towards equator.
(3) no uniformity in the speed of movement of poloidal field towards polar regions.
(4) negligible variation in the poloidal field at the latitude belt $\sim 60^{\circ}$ as compared to those for the polar regions (see Figure 7).
(5) existence of multicells in the meridional circulation. We propose three types of cells one those transport toroidal flux from mid latitude to equatorial belts, second those transport poloidal flux from mid latitude to high latitude belts upto $\sim 60^{\circ}$ and the third those exists in the polar region. How these are created and functioned is not clear to us

# Outline of the Thesis

This thesis mainly deals with the long term variability of solar chromosphere investigated using the Ca-K line profile averaged over 10° in latitude and integrated over the visible 180° longitudes at every 10° interval obtained using high resolution spectrograph at Kodaikanal Tunnel Telescope. The Ca-K line parameters as a function of latitude have been determined on day to day basis for about two solar cycles and the variation of these parameters were examined with latitude and time in detail. Using these variations studies about the meridian flow have been made. Summary of each chapter of the thesis is given in the following:

# Chapter 1

The Sun and in particular chromosphere and its variation with time have been described in this chapter. The work done by various authors in the visible as well as in the UV and EUV wavelength band have been reported in detail. It was noted that various proposed models do explain the variations in the Sun up to some extent but are unable to address some day to day variations in the Sun and exact magnitude of the variation with time and solar cycle. The spectroscopic observations of the Sun as a star in Ca-K line over the last 40 years and images of the Sun in Ca-K line over a century have provided lot of information about the solar variability. But the need to improve the methodology of observations have been addressed. The sources that cause these variations and to estimate the magnitude of the variations by each source detailed high resolution spectroscopic observations with spatial information may lead to better understanding of these variations. The contribution of quiet and polar regions to these variations need to be investigated apart from the variations caused by large scale activity such as sunspots, flares etc. The formation of Ca-K line, formation heights, and properties of various features such as plages, networks and the role of magnetic field in the formation of various features in the chromosphere have been discussed in this chapter.

# Chapter 2

In this chapter I describe the optical design of the Solar Tower Telescope at Kodaikanal and the instrumental set up used to make the observations. Also described are the

methodology and procedure adopted to make the observations on day to day basis whenever the sky conditions permitted. The observational procedure to calibrate the observed data has also been given. The parameters of the instrumental set up are also listed. The procedure followed to analyse the raw data and create set of uniform data for further analysis has been described. Then the details of the automatic software developed to average the profiles for the chosen region on the Sun, normalize the Ca-K profiles, derive the various parameters of the profile such as $K_1$ and $K_2$ widths and K-index and intensity ratios have been provided. Various parameters of Ca-K line as a function of latitude were determined for all the data and the procedure followed to reject the unreliable data due to poor sky conditions has been discussed.

# Chapter 3

The quality and uniformity of the data obtained for the long period of about 25 years have been described in this chapter. The method to compute the Ca-K line parameters for the Sun as a star using the parameters as a function of latitude is discussed to compare the results of these observations with those obtained by other observatories such as Kitt Peak observatory and NSO/Sac Peak observatory. I compared the derived values of $K_1$ and $K_2$ widths from the KKL data with the values obtained from Kitt Peak and NSO/Sac Peak data. Results of this comparison and the long term variations of the Sun as a star using Ca-K line profiles for solar cycles 22 and 23 are presented.

# Chapter 4

In this chapter the data for the active and minimum phase have been analysed separately to compare the parameters during the active and minimum phase of solar cycles. Further, the variations in the Ca-K line parameters have been compared with the variations in the plage areas derived from the Ca-K images of the Sun. From these comparisons we tried to study the contribution of networks in the quiet regions of the Sun.

# Chapter 5

In this chapter data for both the cycles have been considered together but for all the latitudes separately to study the variations as a function of latitude. This chapter deals with the behaviour of $K_1$ and $K_2$ width parameters of the Ca-K line profile at various latitude belts at different phases of the solar cycle. We show how the activity shift in the northern and southern hemisphere. We compute the rate of shift in both the hemispheres to study meridional flows in the chromosphere and find asymmetric behaviour in both the hemispheres. The implications of the rate and direction of shift of the activity with latitude and random behaviour of shift around 60° latitude have been discussed. The variation of activity in polar region with solar cycle phase has also been dealt with.

# Chapter 6

The procedure to model Ca-K line profiles at different latitude and then investigate the variation of $K_1$ width with latitude are described in this chapter. We have used Uitenbroek's RH code to model the Ca-K line profile. We have derived the path length at different $\mu$ in order to compute the profiles at different latitudes for the quiet chromosphere. We have attempted to compute the total network contribution to the line width by considering contribution due to plage areas determined from Ca-K images obtained at Kodaikanal. We found that large database is required to study the variation due to network over solar cycle phase.

# Chapter 7

This chapter contains the summary of entire thesis work. The main conclusions drawn from our studies are outlined here. Some of the possible future prospects of these studies are also listed.

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# List of Publications

1. Study of meridional flow using Ca-K line profiles during solar cycle 22 and 23
   **Sindhuja, G**; Singh, Jagdev; Ravindra, B., 2014, *ApJ*, **792**, 22 – 29.

2. Chromospheric variations with solar cycle phase using imaging and spectroscopic studies
   **G. Sindhuja**; Singh, Jagdev; Priyal, Muthu, 2015, *MNRAS*, **448**, 2798 – 2809.

3. Temporal Variation of Ca-K line profile of the Sun during the solar cycle 22 and 23
   **G. Sindhuja.**; Singh, Jagdev, 2015, *JA& A*, DOI, 10.1007/s12036-015-9330-4, **36**, 81 – 101

4. Multi-slit spectroscopic observations of the solar corona during total solar eclipse of 11 July 2010
   Samanta. T; Singh, Jagdev; **Sindhuja, G**; Banerjee, D., 2015, Submitted

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